INDUSTRIAL CLOUD, FOG, AND PRECIPITATION DURING VERY COLD WEATHER IN EDMONTON

by

Robert B. Charlton and Chan Park
Division of Meteorology, Department of Geography
University of Alberta

Paper Presented at the PNWIS - APCA
1979 Conference
Edmonton, Alberta
November 7-9, 1979

Dr. Charlton is an associate professor of meteorology at the University of Alberta and Mr. Park is working towards his Master of Science degree in meteorology. Their address is: Division of Meteorology, Department of Geography, University of Alberta, Edmonton, Alberta, Canada T6G 2H4.

Boreal Institute
For Northern Studies
Contribution Series No. 97

Pam:551.577 CHA c.1

POLAR PAM 2482

POLARPAM

ABSTRACT

The body of information in this paper is directed to engineers who are involved in the environmental aspects of northern development.

Fog, cloud, and precipitation caused by the petrochemical area of Edmonton, Alberta, were studied during the coldest days of two winters. Typical morning temperatures were between -25 and -40°C. The investigation included a comprehensive heat and vapor emission inventory, field studies of local and microscale cloud physics, and observations of cloud dispersal and precipitation formation. Results were compared with studies of residential Edmonton, oil sands plants, and power parks.

Emphasis was placed on the cloud microphysics of snow which falls from cooling tower plumes. Since this snow was nucleated by drift droplets its development was different than that of natural snowfall. Measured snowfall rates were found to be small compared with those reported during warmer weather when cooling tower emissions may trigger impending natural snowfall.

Introduction

The development of oil sands extraction plants in Northern Alberta has resulted in preliminary studies[1,2] of their ability to produce large amounts of fog and cloud during very cold weather. Because of the remoteness of the oil sands area, studies of the Strathcona County petrochemical complex on the City of Edmonton's eastern boundary were undertaken instead. This industrial complex is the farthest north, for its size, in the western world. The results of this study were expected to be quite different from studies of ice fog in northern communities[3,4] or snowfall from power parks[5,6] in the United States.

The Emission Inventory

A survey of the fifteen largest plants determined typical heat and water vapor emissions on the coldest days of the winter of 1977-1978. The survey included a mass and heat inventory of both process water and cooling towers. Heat and water vapor from fuel consumption were also surveyed.

Table I gives the results of the survey and Figure 1 shows the location and total vapor emission of each plant. The industries lie on a plain which rises about 10 m/km towards the southeast. The river valley averages 1 km across and 25 m deep. Although the survey did not specifically request point emissions, enough data were available along with subsequent field observations, to divide the emissions into low, middle and high levels. Low-level emissions are those which are likely to be involved in plant-site fog. Middle-level emissions rise to around 50 to 100 m and add to the general heat island and humidity of the area. High level emissions from cooling towers and large stacks tend to form clouds on cold days.

For comparison purposes, Table I includes vapor and sensible heat emissions for the City of Edmonton (population ≈500,000) based on ice fog studies[7] and for the oil sands extraction plants in Northern Alberta based on environmental studies[1] and emission inventories.[8] It is apparent in Table I that the total fuel consumption rates of the industrial area, Edmonton, and two oil sands plants are comparable (3557, 6400, and 3144 MW, respectively) as are the total water vapor emissions (599, 258 and 465 $kg s^{-1}$, respectively). It is also apparent that the dominance of low-level emissions from the city should favor fog formation while the oil industries should create both fog and cloud during very cold weather. The question marks under middle level emissions from the city arise from the hypothesis that the depth of low temperature urban fog is of the order of the height of the buildings. Therefore, in the downtown area some emissions would be middle level.

Table II gives water vapor and sensible heat emissions from the major cooling towers in the industrial area. Their total heat load is about 1.2 GW, enough power for 100,000 Canadians to endure a very cold day. Under light wind conditions the center lines of the plumes

48632 BOREAL INSTITUTE LIBRARY

Table I. Emissions from Strathcona industrial area, as reported in survey.

PLANT NAME and (product)	Water vapor, $kg s^{-1}$ and (sensible heat, MW) Low[a]	Middle[a]	High[a]	Total	Fuel consumption MW
ALCAN (coke)	1 (20)	2 (25)	9 (15)	12 (60)	70
BUILDING PRODUCTS (building paper)	2 (11)	-- --	-- --	2 (11)	17
CIL (polyethylene resin)	4 (18)	4 (18)	11 (21)	19 (57)	98
CELANESE[b] (petrochemicals)	20 (120)	30 (80)	100 (200)	150 (400)	800
EDMONTON POWER (electricity)	106 (265)	0.2 (40)	42 (100)	148 (405)	1000
FIBERGLAS (insulations)	0.1 (1)	1 (2)	15 (10)	16 (13)	50
GULF OIL (refinery)	4 (92)	7 (47)	55 (124)	66 (263)	408
IMPERIAL OIL (refinery)	9 (160)	16 (88)	111 (313)	136 (561)	860
KRUPP, G.W.S. (structural steel)	0.1 (2)	-- --	-- --	0.1 (2)	2
PROCOR (railway car repair)	0.2 (6)	-- --	-- --	0.2 (6)	6
STELCO (steel products)	3.5 (8)	6.5 (13)	-- --	10 (21)	41
TEXACO OIL (refinery)	3 (26)	6 (13)	29 (68)	38 (107)	190
TURBO OIL (re-refinery)	0.3 (3)	-- --	-- --	0.3 (3)	3
UNION CARBIDE[b] (gases)	0.5 (3)	-- --	-- --	0.5 (3)	5
UNIROYAL (chemicals)	0.3 (3)	0.5 (1)	-- --	0.8 (4)	7
TOTALS	154 (738)	73 (327)	372 (851)	599 (1916)	3557
EDMONTON CITY (at -35°C)	258 (6400)	? ?	-- --	258 (6400)	6400
TWO OIL SANDS PLANTS (at -35°C)	137 (492)	216 (1342)	112 (349)	465 (2184)	3144

[a]Division into three levels is partly based on visual observations

[b]Estimates based on incomplete data

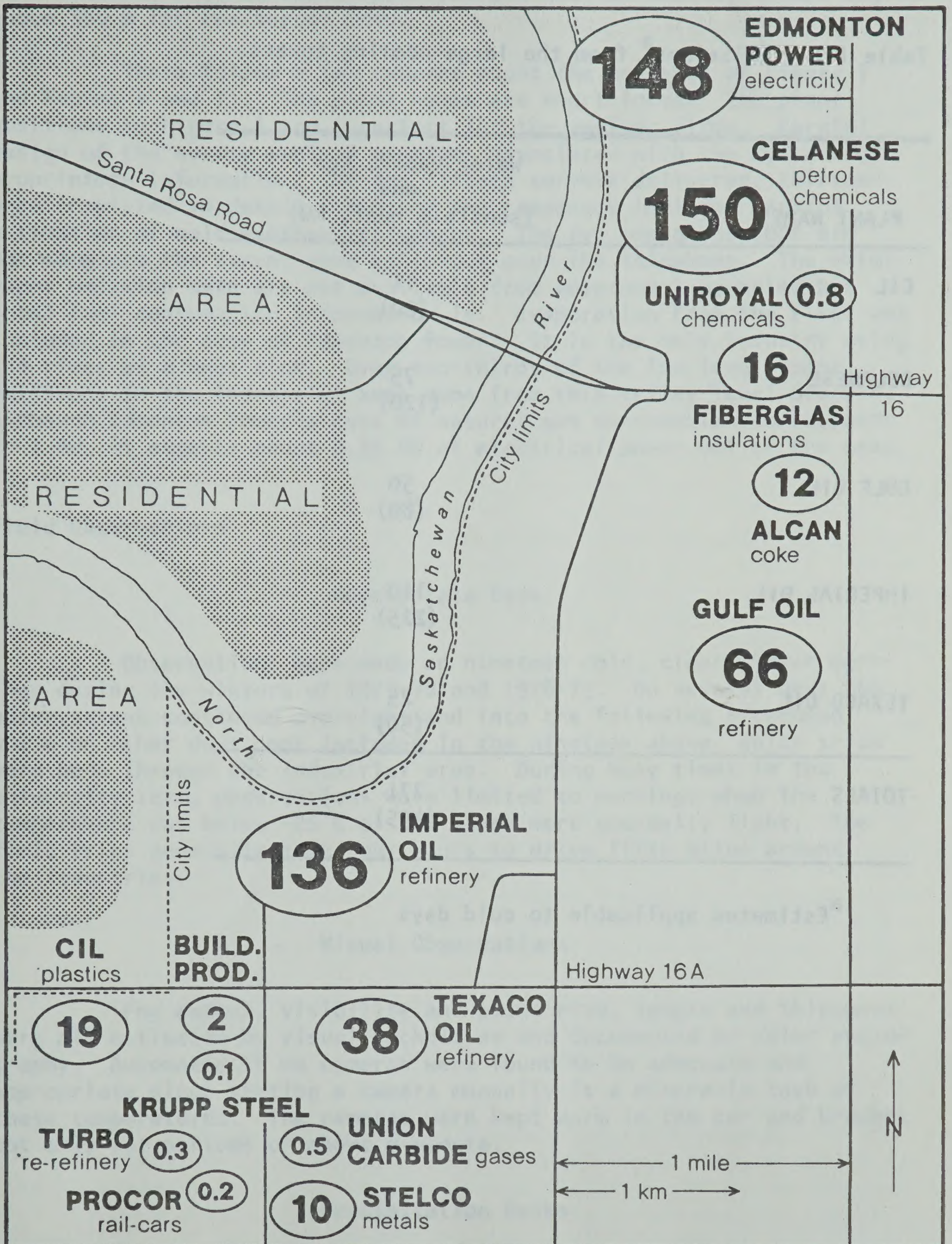

Figure 1
Strathcona industrial area showing major plants, and their water vapor emission rates ($kg\ s^{-1}$) for the winter of 1977 - 78

Table II. Emissions[a] from the large cooling towers.

PLANT NAME	Water vapor, $kg s^{-1}$ and (sensible heat, MW)
CIL	11 (20)
CELANESE	75 (120)
GULF OIL	50 (80)
IMPERIAL OIL	110 (225)
TEXACO OIL	25 (50)
TOTALS	271 (495)

[a]Estimates applicable to cold days

were found to rise to about 150 m for the smaller cooling towers and to above 300 m for the larger ones.

There follow a few remarks about the contents of Figure 1 and Tables I and II. The plant names are short forms. The plant positions in Figure 1 are imperfect for the smaller firms. Careful design of the survey avoided problems associated with the release of proprietory information. Of the fifteen surveys delivered, thirteen were completed in detail. Most of the responses included careful estimation of cold weather influences. The two companies that did not complete the survey gave estimates over the telephone. The water vapor emission data are not available from government agencies but total fuel consumption information is. Evaporation from the river was included in the case of Edmonton Power. It is the only industry using the river as a heat sink. Over two-thirds of the low level vapor emissions in the industrial area come from this valley level process. Although Edmonton Power's rate of natural gas consumption corresponds to 1 GW, it exports about 0.35 GW of electrical power out of the area.

Field Observations

Appropriate Days

Observations were made on nineteen cold, clear winter mornings during the winters of 1977-78 and 1978-79. On several days the observations continued overnight and into the following afternoon while on other days, not included in the nineteen above, quick trips were made through the industrial area. During busy times in the university term, observations were limited to mornings when the temperature was below -25°C or the winds were unusually light. The field trips generally took four hours to drive fifty miles around the industries.

Visual Observations

Fog extent, visibility and plume rise, length and thickness were all estimated by visual techniques and documented by color photography. Automatic 35 mm cameras were found to be adequate and appropriate since setting a camera manually is a miserable task at these temperatures. The cameras were kept warm in the car and brought out only for periods of about a minute.

Precipitation Rates

Snow from industrial plumes was collected in 0.65 m^2 cardboard trays which were set out at several locations downwind of the major cooling towers. Upon returning to the trays the snow was removed and placed in bottles and allowed to melt for later weighing. Most tray exposure times were about two hours but shorter exposures were

made when heavy showers were encountered. Some overnight exposures were also made. A total of 38 tray samples were taken on twelve days and the precipitation rate was calculated in millimeters of liquid water equivalent per hour.

Precipitation Microphysics

Snow crystals on a car's roof were inspected for details down to 50 µm by placing a film inspection lens over top of them. Particle size (habit) and details of the structure were noted.

In order to study the snow microphysics down to 5 µm, glass slides were dipped into a pre-cooled 1% solution of Formvar plastic in 1,2-dichloroethane and the snow crystals were allowed to fall on to the slides for 60 seconds. When the solution is allowed to evaporate at field temperatures it leaves precise plastic replicas of the ice crystals, which could subsequently be counted, classified and photographed at room temperatures. The special techniques needed to make Formvar replicas are described by Schaefer,[9] Strong,[10] and Mason[11] (pages 242 and 243). Replicas were made on ten days and thirty-six were thoroughly analyzed to determine how the snow was being formed in the industrial plumes. Some replicas of natural snow were also made for comparison.

Weather Data Sources

Hourly meteorological observations are available from Edmonton Municipal Airport, Namao Military Airport and Edmonton International Airport which are about 10 km WNW, 15 km NNW, and 25 km SSW of the industrial area, respectively. They were used to compare temperatures, precipitation, and cloud amounts in the city and country to conditions observed in the industrial area. These data helped to confirm that purely industrial phenomena were under observation.

Winds and temperatures at one hundred meters altitude were available from the CBC tower which is located on the eastern edge of the industrial area. Temperatures were also recorded at the base of the tower.

On most mid-mornings minisonde soundings giving winds and temperatures aloft were taken by Alberta Environment at a location 15 km SW of the industries. They were compared to the CBC tower winds and temperatures.

Another check on the vertical wind and temperature profiles came from radiosonde observations taken at 0500 and 1700 LST at Stony Plain, about 50 km to the west.

Temperature data provided by Celanese and wind data from Gulf Oil were also used.

A troublesome aspect of the observations is that humidity measurements are not only inaccurate at these temperatures, they vary considerably between airports due to urban and local influences.

Results of the Field Study

Weather Observed in 5^{o}C Intervals

Table III is a summary of typical weather in the industrial area for 5^{o}C intervals ranging from -15^{o}C to -40^{o}C. No attempt is made to cover all of the temperature, windspeed and wind direction possibilities because there are only 19 mornings of observations. It should be noted again that the data in Table III are summaries of observations taken when the sky was clear in the countryside.

Column 1 gives the five temperature ranges and the number of days found to be suitable for observations in each temperature range.

Column 2 gives the percent of observation days on which ice crystals (IC) were observed to be falling throughout the industrial area and on which ice fog (IF) was widespread. Observations of ice crystals are made by looking towards the sun to see twinkling (scintillation). They are an indicator of air saturated with respect to ice. Ice fog indicates that the air near the surface is saturated over most of the area. Apparently general saturation of the area does not usually occur on clear mornings at temperatures above -25^{o}C. Local fogs were seen to occur at temperatures above -25^{o}C but observations indicate that the industrial heat emissions were usually adequate to cause breezes which ventilate the area and prevent saturation. At temperatures below -30^{o}C ice crystals and ice fog were general.

Column 3 gives the mean and minimum visibilities encountered. At temperatures above -25^{o}C, visibility in most of the industrial area was not restricted and the lowest local visibilities were encountered on two days when industrial snow showers occurred. Between -30^{o}C and -35^{o}C, visibilities were always restricted to an average of 4 km. December 9, 1977, the single morning with temperatures below -35^{o}C was one of the coldest in years. On that date temperatures were below -35^{o}C to several hundred meters in altitude and the cloud water at all levels froze into droplet crystals (called droxtals) of about 10 µm in size. This massive cloud, with its top at about 300 m, spread northward for several kilometers. It was photographed extensively from a tall building downtown where it could be seen above the local ice fog. No snow fell from the cloud. The droxtals appeared to settle out at their theoretical fall speed of 10 m/h. A survey of 10 years of radiosonde data indicated that days with -35^{o}C or colder aloft occur only once every three years in Edmonton but they average three times per year at Fort Smith in northern Alberta. Cloud physicists generally agree that between -32 and -35^{o}C a cloud will quickly turn to ice. Therefore, one can expect many more occurrences of this phenomenon as industry moves northward.

Table III. Weather at industrial area on cold clear mornings arranged according to surface temperatures.[a]

#1 Temp. °C (# days)	#2 % days with IC[b] (with IF[c])	#3 Visibility, mean, km (local, km)	#4 Wind at 100 m, ms^{-1}	#5 Plume length, km	#6 Median Snowfall[d] (Max. Snowfall) 10^{-3} mm^{-1} hr^{-1}
-15 to -20 (4)	25 (0.0)	>10 (0.1 in snow)	6	2.1	9 (129) 6 samples on 1 day[d]
-20 to -25 (5)	20 (0.0)	10 (0.3 in snow)	5	2.1	6 (38) 12 samples on 4 days
-25 to -30 (7)	71 (86)	5 (1)	4	2.4	8 (110) 19 samples on 6 days
-30 to -35 (2)	100 (100)	4 (0.5)	4	2.3	12 (12) 1 sample on 1 day
-35 to -40 (1)	100 (100)	1 (0.05)	4	>10	NA (NA) No samples

[a] All values are observed means, unless noted

[b] Ice crystals; indicates air aloft near ice saturation

[c] Ice fog; indicates surface air near ice saturation

[d] See text for explanation; sampling not done on all days

Column 4 indicates a tendency for lower 100 m wind speeds at lower temperatures. This should probably be interpreted as a tendency towards less night-time cooling with higher wind speeds.

Column 5 indicates that there is little tendency towards longer plumes from the largest cooling towers as surface temperatures range from $-15^{\circ}C$ down to $-35^{\circ}C$ but there is apparently a big increase as the droxtal phenomenon sets in.

Column 6 gives basic results of the 38 tray samples of snow. The median snowfall rate of about 10×10^{-3} mm/h of equivalent liquid water is not large and it does not increase strongly as temperatures fall from -15 to $-35^{\circ}C$. It is of the same order as the mean upward emission rate of 70×10^{-3} mm/h^{-1} from the industrial area (taken as 30 km^2), and is comparable to drizzle measurements downwind of natural draft cooling towers.[12]

The maximum snowfall rate encountered occurred on an essentially calm day, March 1, 1978. On that date, the 100 m wind speed averaged less than 1 m/s for over four hours while the temperature remained just above $-20^{\circ}C$. Heavy snowfalls with visibilities down to 100 m and slippery roads in patches of 200 m were occasionally encountered at around 500 m from the cooling towers. On that morning industrial clouds were so extensive that from some vantage points a weather observer would have declared the sky to be overcast in low cloud even though the countryside was cloud-free. On the other hand, the second heaviest snowfall was encountered nearly 4 km from its source, Gulf Oil's cooling towers, on January 31, 1978 when temperatures were $-27^{\circ}C$ and the winds were averaging 4 m s^{-1} from the northwest. It is believed that the air had picked up substantial moisture over the city on this date before it entered the industrial area. In summary, these snowfalls fell from cooling tower plumes on days when the atmosphere was cold and not inclined to form convective clouds. Therefore, the snowfalls are not of the type where impending showers are triggered by cooling tower plumes as reported by Koenig.[13]

Although the snowfalls from Edmonton's cooling towers were never more than 1 cm deep, they often thoroughly whitened the ground with fragile, low density flakes. These flakes were not always formed in the air since light breezes were seen to cause agglomeration of ice crystals on roadways. These fluffy flakes were often blown from the roadways by the wakes of passing vehicles leaving the pavement bare.

Microphysics of Industrial Snow

Background and Analysis Techniques

Thirty-six Formvar replicas from ten days were photographed and the prints were enlarged to an X25 magnification. In all, 1413 snow particles were analysed according to type, extent of cloud droplet riming, extent of drift drop riming, location of drift drops, and overall particle composition.

Particle typing was done according to the World Meteorological Organization scheme, as described by Mason,[11] with some modifications based on the more detailed classification of Magono and Lee.[14] Particle types which grow by vapor deposition are either hexagonal plates, stellar crystals, columns, needles, spatial dendrites (not six-sided), capped columns or irregular particles. Aggregates of several crystals are called flakes. Snow particles that grow by the riming of super-cooled cloud droplets are called snow pellets (also graupel). Frozen drizzle or frozen cooling tower drift drops are classified as ice pellets. Particles smaller than 250 μm are classified as germ particles. They are abundant at low temperatures but were found to contribute little to the total mass of precipitation. Five size categories between 250 μm and 8 mm were used; each with its maximum size double its minimum size.

The degree to which each particle had grown by riming was compared to its crystalline growth by vapor deposition. Generally speaking, the conditions favoring growth of a snow pellet as opposed to crystal growth are either a large cloud water content or a drift drop embryo because it can collect cloud droplets efficiently. If ice crystals predominate they have a tendency to aggregate into snow flakes which are also good rimers. However, flakes are usually formed in regions of the plume with relatively low water content.

Although cloud droplets are readily cooled to -30°C before they freeze, drops larger than 100 μm have a rapidly increasing probability of freezing as their temperature falls from -20 to -25°C.[11,15] Summaries of cloud parameters required to grow a drift-sized drop by the coalescence of cloud droplets indicate that cooling tower plumes do not have the required parameters.[11,16] Therefore, the large frozen drops found in cooling tower plumes are surely of drift origin.

Summary of the Observed Snow Particles

Figure 2 illustrates some of the growth possibilities of a precipitation particle in a cooling tower plume. It shows the embryo of the ice particle to be a frozen drift drop which becomes the center of a competition between its riming to a snow pellet and its growth to a six-sided crystal. In the figure, crystalline growth appears to have prevailed. As growth of the six-sided plate begins, the particle's fallspeed would be reduced as would be its ability to collect rime. Riming of plates is summarized in Pruppacher and Klett[16] where they show that when the plate has grown to a few hundred microns, the particle would regain its ability to rime along its edges and particularly at the corners as seen in Figure 2. If the cloud-water content of the plume is high enough, heavy riming can lead to a large snow pellet forming around the crystal.

Table IV shows the size distribution of the 1413 snow particles and 1342 drift droplets investigated. The median size of snow particles is between 250 and 500 μm and that of drift drops is between 125 and 250 μm. The mass-weighted median diameter of snow is in the 1 to 2 mm

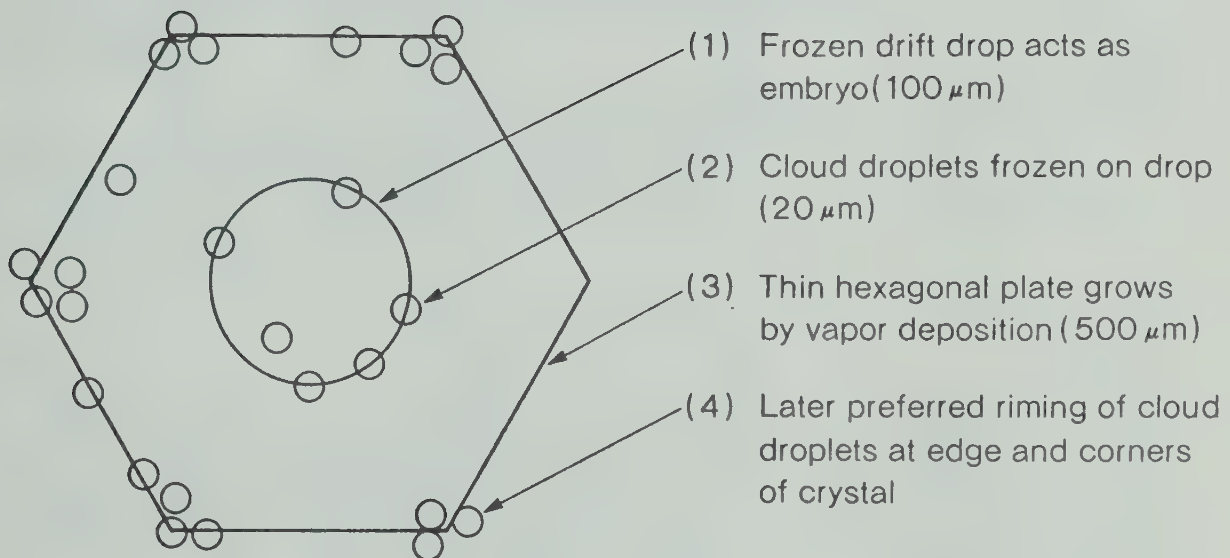

Figure 2
Typical growth modes of precipitation particle in a cooling tower plume at -25°C

Table IV. Size Distributions of Snow Particles and Drift Particles

Category	% Snow Distribution	% Drift Distribution	% Snow with Drift Embryo
0 - 125 µm	16	27	26
125 - 250 µm	29	54	
250 - 500 µm	27	14	
500 - 1000 µm	21	5	47
1 - 2 mm	6	0.3	
2 - 4 mm	1	0.1	
4 - 8 mm	0.3	0.0	
Total %	100	100	
Investigated	1413	1342	453

range while that for drift is in the 0.5 to 1 mm range because a few large drift droplets were encountered. Excluding the large drift droplets, the drift size distribution compares favorably with that reported by other authors.[17,18] Although most of the 1342 drift droplets were rimed onto a snow particle, 453 acted as the center for snow particle growth. It was sometimes impossible to determine whether a snow particle had a drift embryo. Nevertheless, at least 26% of snow particles smaller than 500 μm and 47% of those larger positively originated as a frozen drift particle. An investigation not summarized in Table IV revealed that of the 422 particles larger than 500 μm, 161 were single crystals of which only 25% originated as drift. This implies that large crystals tend to grow from other than drift embryos. It is tempting to discuss other details of the snow particle study. However, this report can be adequately summarized by stating that in all probability, more than one-half of the snow particles originated as cooling tower drift drops.

For comparative purposes, several Formvar replicas of natural snow particles were made on days with temperatures typical of the industrial field observations. None of the natural snow particles revealed drift size drops (greater than 50 μm) in their center or rimed onto their edges.

Summary

The Strathcona industrial area is a suitable place from which to investigate the potential for the formation of fog, cloud, and snow by industries at more northerly locations. If latent heat is included, the area's total power loss to the atmosphere is more than 3 GW, a figure which is of the order of that of the city of Edmonton or existing industrial complexes.

Fog does not usually restrict visibility throughout the Strathcona industrial area at temperatures above -25^{o}C. Below that temperature, clear morning visibilities are restricted throughout the area on most days with visibilities reduced locally to a few hundred meters. Observations indicate that the thermal breezes caused by the larger plants prevent thick fog throughout the area until temperatures of -35^{o}C are reached, whereupon deep ice fog sets in with visibilities dropping locally to 50 m.

Cooling tower plumes are usually about 2 km long at temperatures above -35^{o}C but at lower temperatures the plumes become very persistent as an ice fog phenomenon sets in. On days with very calm winds and moderately low temperatures the plumes can become wide-spread to the extent where, from certain vantage points, the sky appears to be overcast.

Precipitation rates from the large plumes are typically 10^{-2} mm/h of water equivalent which is not enough to cover roadways. However, snowfalls of more than 0.1 mm/h were encountered and they did whiten roadways and make driving hazardous when the visibility fell below 100 m.

The heaviest snowfalls occurred within 1 km of the source on a day with very calm wind conditions and temperatures of -18°C. Surprisingly, heavy snowfalls were also encountered at a distance of nearly 4 km on mornings with average winds and -27°C temperatures.

Formvar plastic replicas were found to be a convenient way to document the microphysics of the snow particles. They reveal the size distributions of the snow particles and the drift drops as well as the shape and degree of riming of the particles. The replicas indicate that snowfall from cooling towers is highly dependent on drift droplets under the conditions studied.

Future Work

Work is continuing on an air column trajectory model which might predict the formation of fog and a plume dispersal model which would give cloud water distributions for a snow particle growth model.

Future field work should include portable temperature and humidity measurements. They are expected to reveal rather sharp variations in space and time.

Acknowledgements

This research was supported by grants from the Boreal Institute for Northern Studies, University of Alberta and from the Atmospheric Environment Service, Government of Canada.

References

1. B.R. Croft, A. Lamb, and R.N. Dawson, "A preliminary investigation into the magnitude of fog occurrence and associated problems in the Oil Sands area," Sub-project M.E. 3.3. AOSERP Report No. 9, Alberta Environment and AES, (1976).

2. W. Murray and T. Low, "An observational study of fog in the AOSERP study area," Alberta Oil Sands Environmental Research Program (AOSERP), Alberta Environment, (to be published in 1979).

3. C. Benson, "Ice fog: low temperature air pollution," CREEL Report No. 121, U.S. Army, Hanover, N.H., (1970).

4. E. Robinson, W. Thuman and E. Wiggons, "Ice fog as a problem of air pollution in the Arctic," Arctic 10, 89, (1975).

5. M.L. Kramer, D.E. Seymour and M.E. Smith, "Snowfall observations from natural-draft cooling tower plumes," Science 150, (Sept. 1976).

6. W.M. Culkowski, "An anomalous snow at Oak Ridge, Tennessee," Mon. Weather Rev. 90, 194, (1962).

7. K.D. Hage, "Urban growth effects on low-temperature fog in Edmonton," Boundary Layer Meteorology 2, (1972).

8. SNC Tottrup Services Ltd., "Sources and emissions inventory for the Alberta Oil Sands area," Sub-project ME 2.2. AOSERP, Alberta Environment and AES, (1977).

9. V.J. Schaefer, "Preparation of permanent replicas of snow, frost and ice," Weatherwise 17, 6, (1964), 278-287.

10. C.L. Strong, "The amateur scientist - on preserving the shapes of snow crystals by catching snowflakes in dissolved plastic," Sci. Am. 214, 3, (1966), 120-126.

11. B.J. Mason, "The physics of clouds," 2nd edition, Clarendon Press, Oxford, (1971), 671 pp.

12. A. Martin and F.R. Barber, "Measurements of precipitation downwind of cooling towers," Atmospheric Environment 8, 4, (1974), 373-381.

13. L.R. Koenig, "Self-precipitation of snow from cooling towers," Preprints of the Conference on Cloud Physics and Atmospheric Electricity, Issaquah. Am. Meteorological Soc., (1978), 426-429.

14. C. Magono and C.W. Lee, "Meteorological classification of natural snow crystals," J. Faculty Sci., Hokkoaido Univ., VII (Geophysics), 11, No. 4, (Nov., 1966), 728-736.

15. H.G. Leighton, "The ice phase and the evolution of cloud droplet spectra," Atmosphere 15, 2, (1977), 79-88.

16. H.R. Pruppacher and J.D. Klett, "Microphysics of clouds and precipitation," D. Reidel Pub., Dordrecht, (1978), 714 pp.

17. A. Martin and F.R. Barber, "Some water droplet measurements inside cooling towers," Atmospheric Environment 8, 4, (1974), 325-336.

18. Steven R. Hanna, "Personal communication," Air Resources Atmospheric Turbulence and Diffusion Laboratory, NOAA, Oak Ridge, Tenn., (1978).

Date Due

DATE LOANED | BORROWER'S NAME | DATE DUE

48632

BOREAL INSTITUTE FOR NORTHERN STUDIES, LIBRARY
THE UNIVERSITY OF ALBERTA
EDMONTON, ALBERTA T6G 2E9
CANADA

University of Alberta Library
0 1620 0333 0519